BEAM-BEAM STUDIES FOR HL-LHC*

A. Valishev#, FNAL, Batavia, IL 60510, USA
D. Shatilov, BINP, Novosibirsk 630090, Russia
T. Pieloni, CERN, Geneva, Switzerland

Abstract

The analysis of beam-beam effects for the High Luminosity LHC upgrade is in progress as a part of HiLumi LHC Design Study. We report on the current status of beam-beam simulations with the particular emphasis on single and multi-particle weak-strong tracking studies. We evaluate the LH-LHC performance scenarios, and outline the plan of further research.

MOTIVATION AND APPROACH

A major upgrade of the Large Hadron Collider aiming at a significant increase of its luminosity beyond the design value is planned for around 2020. The machine configuration, called High Luminosity LHC (HL-LHC) will incorporate a number of technological advances bringing the beam intensity, brightness and overall accelerator precision to an unprecedented level. The global HiLumi LHC Design Study is in progress with the goal of delivering an integrated design to facilitate the upgrade [1]. Quite naturally, the examination of beam dynamics aspects constitutes an essential part of the effort. In the HiLumi structure, Work Package 2 covers accelerator physics subjects and combines the following Tasks: Coordination and Communication; Optics and Layout; Intensity Limitations; Beam-Beam Effects; Beam Parameter and Luminosity Optimization. The Tasks work in close collaboration with each other to enable the development of a coherent view on the beam dynamics. The goal of Beam-Beam Task is to evaluate the possible performance limitations arising from beam-beam interactions, to define key parameters such as minimum required beam separation and maximum acceptable beam brightness values and to identify optimum beam configurations for the different operating scenarios.

The studies of beam-beam interactions at HL-LHC are grouped into two categories: the weak-strong (incoherent) and the strong-strong (coherent) effects. The proposed values of beam brightness at HL-LHC suggest that the weak-strong effects are more likely to result in performance limitation through the creation of resonances causing particle losses and emittance growth. As such, the incoherent effects are the focus of the present report. For the strong-strong effects see e.g. Ref. [2, 3].

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#valishev@fnal.gov

PERFORMANCE SCENARIOS

A detailed description of the baseline HL-LHC scenario can be found in Refs. [4, 5]. Here we present the parameters relevant to the simulations reported further.

The so-called ‘stretched’ baseline HL-LHC scenario presumes that at the beginning of a high-energy run (fill), the beams collide at IP1 and IP5 (Atlas and CMS experiments) at the full crossing angle of 590 μrad. Due to the large geometrical reduction, the total beam-beam tune shift is quite moderate and does not exceed 0.015 for the case of 3 head-on collisions. The transverse separation at long-range collision points is 12.5 beam sigma. As the beam intensity decays due to the luminosity burn-off, the bunches are gradually tilted with respect to the reference trajectory (crabbed) using RF crab cavities, which results in a head-on collision at the end of the fill. This achieves a constant (leveled) luminosity of 5×10^{34} cm^{-2}s^{-1}, thus allowing to maximize the luminosity integral. The beta-function at IP1/5 during leveling remains constant at 15 cm.

Table 1: ‘Stretched’ baseline HL-LHC parameters for 25ns bunch spacing

Parameter	Value
Protons/bunch	2.2×10^{11}
Number of bunches	2808
Crossing angle	590 μrad
β*	15 cm
Normalized emittance	2.5 μm
Energy spread	1.2×10^{-4}
Bunch length	7.5 cm
Beam-beam tune shift per IP	0.0033

In the baseline HL-LHC scenario the luminosity is leveled such that the number of events per crossing (pile-up) does not exceed the limit set by experiments. However, it was recently recognized that the longitudinal pile-up density (the number of events per unit length or unit time) also needs to be limited. This can be achieved through maximizing the length of luminous area by keeping the bunches always colliding fully head-on (crabbed). The luminosity leveling in this scheme is performed by the change of beta-function, i.e. β*=70 cm at the beginning of a fill, and then is gradually reduced to 15 cm.

SIMULATION TOOLS

The weak-strong beam-beam simulations for HL-LHC were performed with two particle tracking codes: SixTrack [6] and Lifetrac [7]. Both codes have been extensively used for the development of such colliders as the Tevatron, DAFNE, and LHC, and have been well tested against available experimental data. Nevertheless, we performed additional benchmarking in order to ensure consistency of simulations. For example, Fig. 1 presents the Dynamic Aperture (DA) simulation for HL-LHC lattice with multipole errors in the absence of beam-beam interactions.

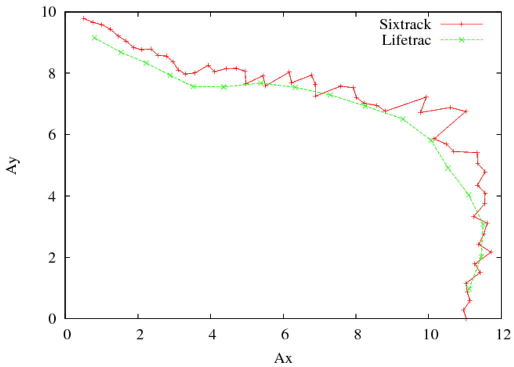

Figure 1: Dynamic aperture (Ax, Ay in units of beam σ) for HL-LHC lattice with multipole errors without beam-beam, simulated with two codes.

The two codes treat machine lattice with a symplectic thin-lens approach, and account for full set of machine features, including the focusing chromaticity and high-order multipole errors. The beam-beam kicks are realized through analytical formulae (the so-called Hirata formalism).

The standard figure of merit for the evaluation of performance is the dynamical aperture for particles with momentum deviation of 2.7×10^{-4}, based on 10^6 turns of tracking. However, a recent application of the Frequency Map Analysis [8] to beam-beam interactions [9] provides a useful insight into the dynamics of a system with much less intensive simulations. Throughout the report we provide comparisons of the two approaches.

BASELINE SCENARIO RESULTS

Figures 1, 2 present simulation results for the baseline scenario. The color on FMA plots depicts the tune variation along a particle's trajectory over 2^{12} turns (momentum deviation for these FMA simulations was zero). The logarithmic scale is provided in Fig. 1 on the right. One can see that the tune footprint is small and is not densely populated with resonances. The DA results based on 10^6 turns generally agree well with area in FMA plots where tune jitter is large, and resonances overlap (Chirikov criterion [10]).

Fig. 4 shows the DA for various options of HL-LHC optics as a function of crossing angle. The target minimum DA for a robust design is 6 σ, which determines the choice of crossing angle for the baseline scenario.

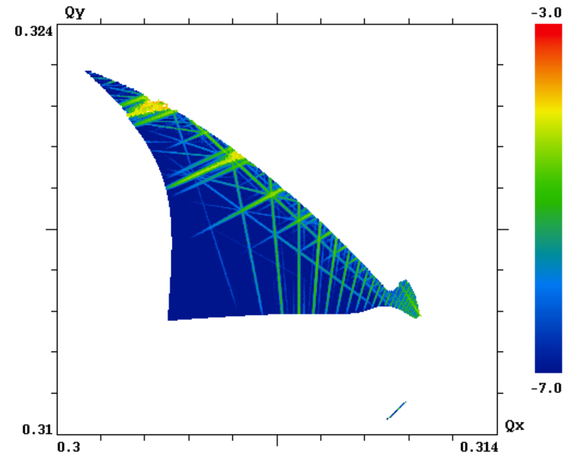

Figure 2: FMA plot in tune space (tune footprint) for HL-LHC baseline scenario.

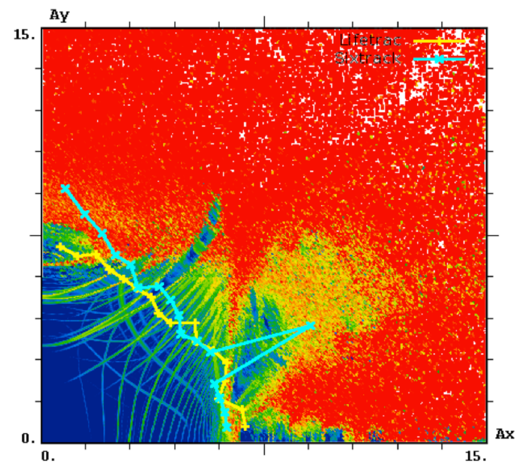

Figure 3: FMA plot in amplitude space for HL-LHC baseline scenario. Yellow line – Lifetrac dynamic aperture, cyan line – SixTrack dynamic aperture.

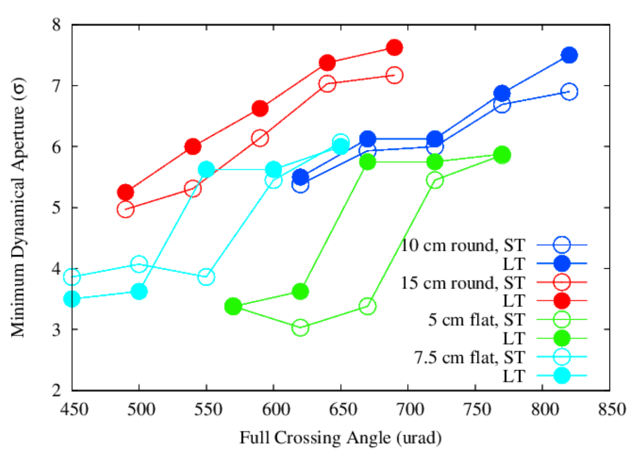

Figure 4: Minimum dynamical aperture for different types of HL-LHC optics as a function of crossing angle. ST – SixTrack, LT – Lifetrac data.

BETA-FUNCTION LEVELING SCENARIO

The alternative leveling scenario is more demanding with respect to beam-beam interaction due to a relavively large beam-beam tune shift at the beginning of a fill (ξ=0.034). However, the results in Figs. 5-7 suggest that at least for the case of machine without multipole imperfections, the DA is not reduced below 6 σ. The 7th order resonance does not cause significant diffusion of the core particles. The overlapping 10th and 13th order resonances cause some emittance growth, which reduced the luminosity lifetime to approximately 20 hours. However, it is likely the effect of these resonances could be mitigated by a careful choice of the betatron tune working point. We also explored the possibility to reduce the crossing angle towards the end of a fill, when the bunch intensity decays to Np=0.95×10^{11}, to 480 μrad (10 σ separation), and found that DA in this case remains over 6.5 σ.

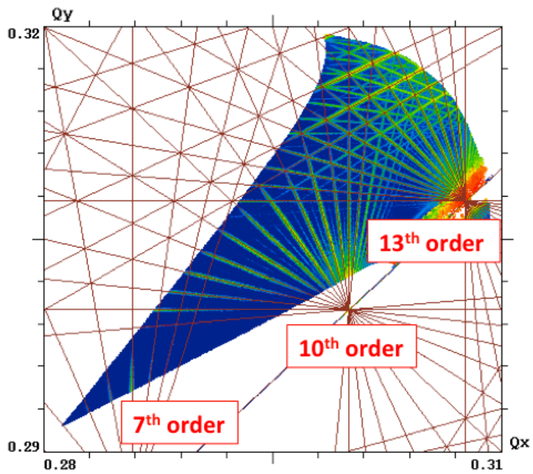

Figure 5: FMA plot in tune space for full head-on collision at IP1/5. β*=15 cm, crossing angle 590 μrad (12.5 σ separation).

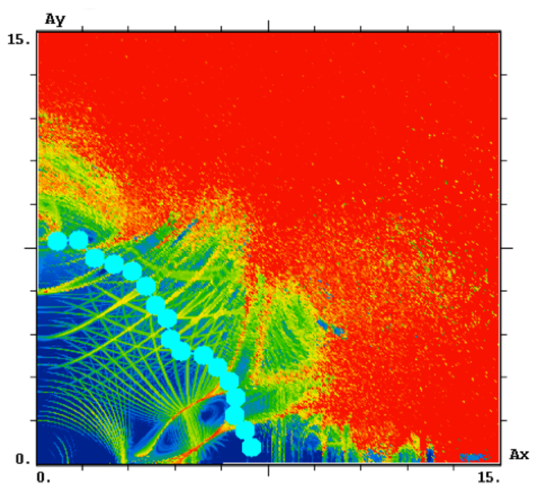

Figure 6: FMA plot in amplitude space for full head-on collision at IP1/5.

SUMMARY AND OUTLOOK

The weak-strong simulations of beam-beam effects in HL-LHC using two particle tracking codes demonstrate robustness of the baseline operational scenario. The dynamic aperture predicted by both codes is over the reference value of 6 σ for a machine with no multipole imperfections. Studies of an alternative luminosity leveling scenario making use of beta-function leveling and full head-on interactions, predict that despite the significantly larger beam-beam parameter in this scheme, the dynamical aperture is well within the specified limit. The alternative scheme may allow a decrease of the crossing angle an, consequently, the required crab-cavity voltage.

Future effort will be concentrated on the studies of sensitivity of the proposed schemes to machine imperfections. We also plan to investigate other options of achieving lower pile-up density, such as longitudinal beam density shaping.

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